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SCALING RELATIONSHIPS FOR MICROSCALE TO MEGASCALE IMPACT CRATERS

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ABSTRACT

An analysis of scaling relationships is presented for impact craters formed in liquids, rocks, and metals. The roles of target strength and gravitational acceleration are considered. The controversy of whether penetration varies with the two-thirds or one-third power of the impact velocity is suggested to be academic until the effects of target strength are firmly established.

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INTRODUCTION

Impact cratering in rocks and the related phenomena are of interest to workers in the geosciences and have been studied for a number of years at the NASA's Ames Research Center in a cooperative program of research with the U. S. Geological Survey. Particular emphasis has been placed on the interpretation of the effects of impact of interplanetary debris with the lunar surface. This emphasis has focused attention on problems of scaling the results from small laboratory craters across more than 12 orders of magnitude; i.e., the absence of a lunar atmosphere requires attention to the entire spectrum of interplanetary particles and bodies which crater the lunar surface with holes ranging from micron-sized pits to major geologic structures measured in hundreds of kilometers.

The subject of scale effects is new to the field of hypervelocity impact. To the authors' knowledge the existence of scale effects was unsuspected or at least had not been demonstrated until Denardo and Nysmith[1] reported their observations of scale effects for craters in aluminum. Subsequently, Moore et al.[2] presented evidence for scale effects in impact craters formed in rock; significantly, they related the scale effect to a change in effective target strength with crater size.

It is the purpose of this paper to describe some results from an extension of the analysis presented in reference 2 based on a more general approach to the problem. The principal thought throughout has been to explore factors or parameters which are important in establishing scaling relationships applicable over the range of sizes appropriate for lunar craters. Although certain results are pertinent to the geoscience interests, the role developed for target strength has special significance to the over-all subject of hypervelocity impact.

ANALYSIS

Craters Formed in Water

It is instructive to consider first cratering in liquids. Engel[3] and Moore et al.[4] have reported theoretical and experimental studies of transient cavities produced in water by water drops. They have shown that there are two primary energy sinks, which result from surface tension and hydrostatic pressure, during the formation of water craters. Briefly, from their studies, one can write for hemispherical geometry

$$\text{Formation energy} = 2\pi \int_0^p (\text{stress}) r^2 \, dr \tag{1}$$

where r is crater radius, p is the final or penetration radius, and the stress serves to provide the resistance against which energy must be expended to form the crater. The formation energy is $2\pi T p^2$ for the stress $2T/r$ attributable to surface tension T. Against the mean hydrostatic pressure $\rho g r/2$, where ρ is mass density and g is gravitational acceleration, the formation energy becomes $\pi \rho g p^4/4$. The sum of these two energies is (approximately) the total energy E required to form the crater

$$E \approx \frac{\pi}{4} (8Tp^2 + \rho g p^4) \tag{2}$$

and after the displaced or ejected mass M_e is introduced

$$E \approx \left(\frac{3}{2\pi\rho}\right)^{2/3} \left[8T{M_e}^{2/3} + \left(\frac{2}{3\pi}\right)^{2/3} \rho^{1/3} g {M_e}^{4/3}\right] \tag{3}$$

Equations (2) and (3) are interesting in that the relative importance of the two terms in the brackets depends on the size or scale of the crater being considered. For very large craters ($M_e \gg 1$ gram), the second term due to hydrostatic stresses becomes the dominant term and

$$M_e \propto E^{3/4}$$

This is also equivalent to writing

$$p \propto E^{1/4} \tag{4}$$

or when E is related to the kinetic energy E_p of a projectile traveling with a velocity V

$$p \propto V^{1/2}$$

Equation (4) is a form familiar to workers who have studied large explosive cratering events[5] and is categorized as indicating a fourth-root or gravity scaling. For this type of scaling the energy spent during crater formation is used solely to raise large masses of material out of the cavity; the energy expenditure is directly proportional to the gravitationally induced overburden (lithostatic or hydrostatic) pressures and, hence, the name "gravity scaling." This type of scaling, however, is not valid for very small craters. For water craters the term in the brackets contributed by surface tension becomes the dominant factor when $M_e \ll 1$ gram. If the hydrostatic term is neglected, therefore,

$$M_e \propto E^{3/2}$$

and the equivalent forms are

$$p \propto E^{1/2}$$

$$p \propto V$$

These results are closely related to those described by Moore et al.[2] for rocks in which the Griffith theory[6] of failure in brittle substances is employed to account for a scale effect resulting from a change in effective target strength with size of the crater. Indeed, if one uses a stress proportional to $r^{-1/2}$ as suggested by the Griffith theory, it is easily shown that[2]

$$M_e \propto E^{6/5}; \qquad p \propto E^{2/5}; \qquad p \propto V^{4/5}$$

Thus if one accepts the suggestion that the observations reported in reference 2 are explicable, at least in part, by the effects of changing target strength, then the stress resulting from surface tension becomes closely analogous to some measure of target strength for craters formed in liquids. The authors suggest "strength scaling" is, perhaps, an appropriate terminology for this regime.

With an assumption that $E = 1/2Ep$, based on the Charters-Summers theory,[7] the energy requirements for water craters predicted by equation (3) are compared with the available experimental data in figure 1. The agreement between experiment and equation (3) is gratifyingly good (see also ref. 4) and it is noteworthy that the experiments all fall in a transition region between exclusively surface tension scaling and exclusively hydrostatic pressure scaling. The $p \propto V^{2/3}$ variation observed for water craters that is described in reference 4 would appear to be a highly fortuitous result and it does not represent any confirmation of the much debated 2/3 power law.

Craters Formed in Solids

A somewhat similar approach to examine scaling laws and effect of target strength for rock and metal craters will now be carried out using a modification of the Charters-Summers theory for crater formation. The cratering model for this theory involves the transfer of momentum and energy from the projectile into the target medium to form a thin shell of compressed mass that expands radially outward against the restraining forces established by stresses produced during deformation of the target material. The model is not, nor was it ever intended to be, a sophisticated description of the cratering process, but its simplicity is a prime virtue. The basic physics of crater formation are exposed to analysis -

i.e., the role of target deformation with due consideration to target strength - without resorting to a complicated mathematical or physical model.

The reader is referred to reference 6 for a more complete discussion of the theory. It is sufficient here to note that starting with an expression similar to equation (2), Charters and Summers introduce the concept of a mean deformation strength $\overline{s}$. In effect, they define

$$\overline{s} \propto \int_0^p s(r)\,dr$$

so that $\overline{s}$ may be assumed to be independent of r for any given cratering event. The deformation strength can, however, vary from any one event to another. On this basis the Charters-Summers theory yields

$$M_e \propto Ep/\overline{s}$$

with the result that for a constant $\overline{s}$

$$M_e \propto E_p; \qquad p \propto E_p^{1/3}$$

After the projectile diameter d was used to normalize the penetration they obtained the commonly used power law

$$\frac{p}{d} \propto V^{2/3}$$

Material strength, however, is known to be a function of many variables including strain rate, confining pressure, temperature, and, as previously discussed, the size of the sample of material under stress. In the subsequent paragraphs, the Charters-Summers theory is used to explore qualitatively the manner in which such factors may affect impact cratering results.

It is to be noted that both strain rate and confining pressure increase with increasing impact velocity. Moreover, material strengths generally increase with increases in strain rate and confining pressure. Values for the mean deformation strength $\overline{s}$, therefore, should be expected to increase as the impact velocity increases. It is convenient, for present purposes only, to assume a functional relationship between $\overline{s}$ and V that reflects the expected effects of strain rate and confining stress. Thus we assume

$$\overline{s}(\text{strain rate and confining stress}) \propto V^{mV} \qquad (5)$$

where the equation is introduced with the understanding that $m > 0$ and it is emphasized that the equation only illustrates that a mean deformation strength $\overline{s}$ will probably increase with the impact velocity because of the changes in the strain rates and confining pressures.

In a somewhat similar manner, the effects of size on $\overline{s}$ can be expressed in a form suitable for insertion in the Charters-Summers theory. The weakest link theory of Evans and Pomeroy,[8] a statistical solution to changes in strength with size for materials containing cracks and defects, suggests the rupture stress R is inversely proportional to some power of the test specimen size X.

$$R \propto X^{-n}$$

Values for n would vary between 0 and 1/2 depending on the type of flaws in the specimen and the nature of their activation. When the rupture stress is taken to be proportional to $\overline{s}$ and the penetration p is taken to be a representative dimension for the specimen size, the effect of internal defects on the mean deformation stress is

$$\overline{s}(\text{defects}) \propto p^{-n} \propto M_e^{-n/3} \qquad (6)$$

Combining equations (5) and (6), one finds that

$$\overline{s} \propto V^{mV} p^{-n}$$

and an extended Charters-Summers theory can be written as

$$M_e \propto \left(\frac{E_p}{V^{mV}}\right)^{\frac{3}{3-n}}$$

or its equivalent forms

$$\left.\begin{aligned} p &\propto \left(\frac{E_p}{V^{mV}}\right)^{\frac{1}{3-n}} \\ \frac{p}{d} &\propto d^{\frac{n}{3-n}} V^{\frac{2-mV}{3-n}} \end{aligned}\right\} \qquad (7)$$

The most significant result from this simple extension of the Charters-Summers theory is the indication that scale effects can arise from changes in both the impact velocity and projectile size. For the special case m = n = 0 originally treated by Charters and Summers, there is a unique 2/3 power velocity scaling law that is independent of projectile diameter. For real substances, however, m and n probably will never be zero and no single power law can be anticipated to be valid for all materials and conditions; many different scaling laws or, perhaps more correctly, a continuous change in scaling relationships must be expected.

With reference to equation (7), for any given target and projectile combination the value of the exponent for the velocity should decrease as the impact velocity increases. This effect will decrease the rate at which the normalized penetration increases with velocity and is a manifestation of the increased effective target strength produced by higher strain rates and confining pressures. Such trends are clearly evident in the experimental data,[2,9] and it is significant that if these trends are attributable even in part to strength effects, comparisons between experimental and hydrodynamic code values for the velocity exponent are open to question. Initial values for the velocity exponent are predicted from equation (7) to be between 4/5 and 2/3, values appropriate, respectively, to $n = 1/2$ predicted by the Griffith defect theory and $n = 0$ for an ideal material with no defects.

If the velocity is maintained constant for a given target and projectile combination, equation (7) predicts that the normalized penetration should increase with projectile size. It is interesting to note that such an effect has been reported by Denardo and Nysmith[1] for impact of aluminum into aluminum. They found that the value for the exponent of d was 1/18. This corresponds to $n = 3/19$ (or $n = 0.157$) in equation (7) and is appropriate for a metal. With a value of 1/2 corresponding to the Griffith defect theory, the exponent of d probably will not exceed 1/5; the normalized penetration, therefore, should never be a strong function of the projectile size.

CONCLUDING REMARKS

Cratering data for rocks (both impact and explosive) and Denardo and Nysmith's aluminum data are compared in figure 1 with the water crater data and theory. Only the data for rocks cover a sufficiently broad range of energies to afford a full comparison with the theoretical curve for water, but it is clear that there are striking similarities between water and the solids. For the lower range of energy expenditure, extending down to sputtering of individual atoms for rocks and the energy required to evaporate one molecule of water, the ejected mass M_e is proportional to some power of the energy E_p greater than 1. This result is not inconsistent with the concept that there are changes in the effective target strength with the scale of the event. Over the upper range of energy the ejected mass from rocks is proportional to a power of the energy less than 1 and the over-all trends are remarkably consistent, with virtually a pure gravitational scaling developing into a transition zone with strength scaling.

The role of target strength, it is believed, cannot be overemphasized; until this role is firmly established, values for velocity power law scaling relationships will be purely academic.

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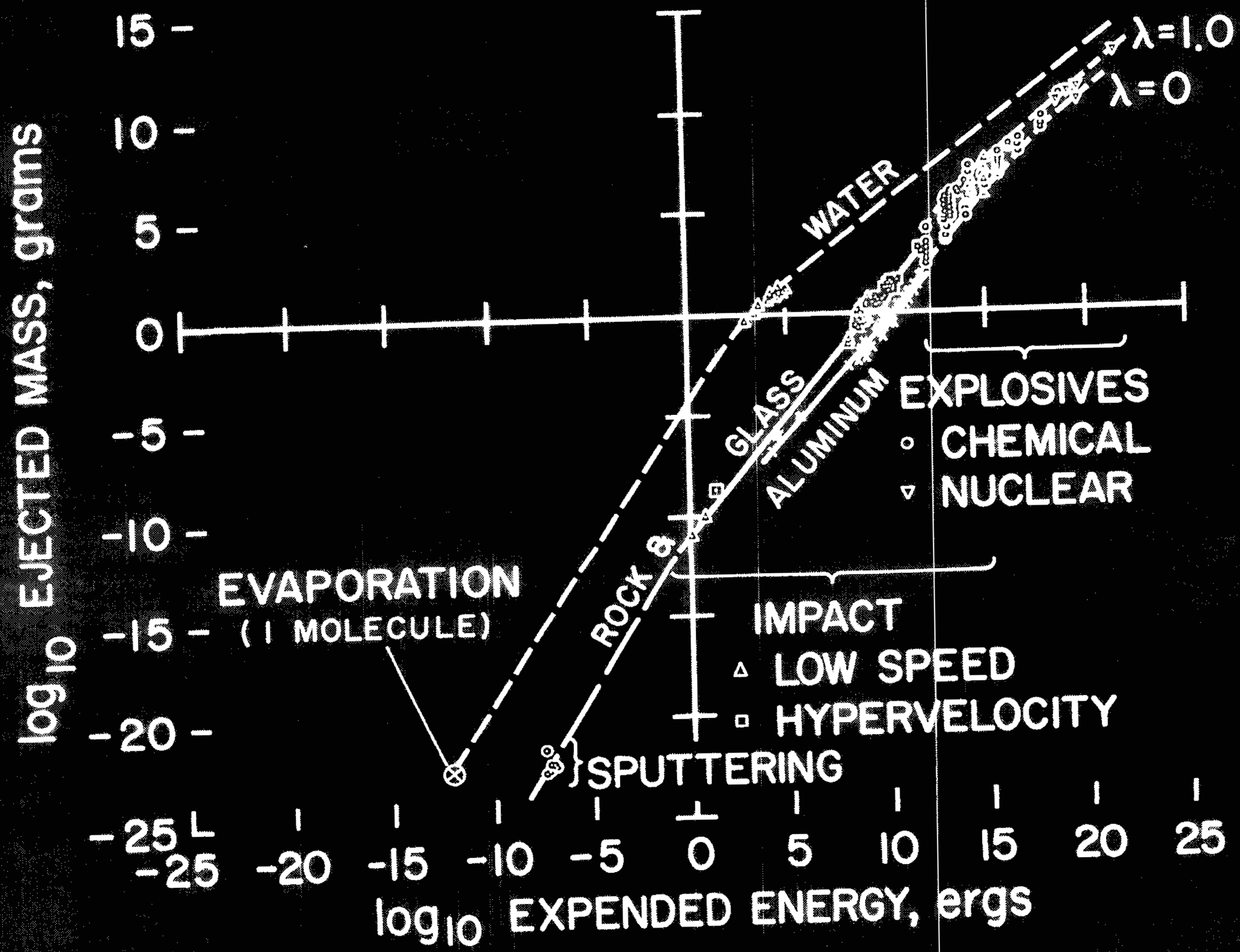
FIGURE LEGEND

Figure 1.- Variation of the ejected mass M_e with the expended energy E_p for craters formed in water, rocks, and aluminum. The symbol λ denotes the scaled depth of burst for explosive craters and is equal to the ratio of the depth of burial for the explosive, measured in feet, to the cube root of the energy release, expressed in pounds of TNT.



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